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How I Wrote My Prospectus

Writing a prospectus can be daunting – it took me several months to come up with projects and define the science goal that unites them. I got the initial ideas after talking to my advisor about upcoming projects in our research group. I read some examples from past students in my department, but there was not much guidance on how to prepare it. Much of the prospectus process was reading literature articles to grasp the big picture and how my projects fit in.

Advice for Prospectus Writers

I recommend working on the prospectus and the oral exam slides at the same time. I found that they were different ways of sketching out the same plan. Think about what your committee will be looking for: the key innovation in your project, the scope and timeframe, and feasibility. Don't be afraid to get feedback from more sources: not only your advisor and research group, but also other (senior) students from your department and GWL consultants.

Probing the Formation of Ultra-diffuse Galaxies with Observations

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Contents

Introduction

Ultra-Diffuse Galaxies are defined to have large physical size ($\geq$ 1.5 kpc) and low surface brightness. Since this definition is observational and based on their extended nature, UDGs may not be a homogenous group. UDGs have the stellar mass of dwarf galaxies but the physical size of the Milky Way, and this makes them good probes of dark matter. They should be DM dominated at all radii, and compared to ultra-faint dwarf galaxies, their expected large internal velocities (~30 km/s) can be measured to better relative precision. UDGs have globular clusters (GCs) which provide observational probes to get the velocity dispersion. They are found in all environments, both isolated and in groups and clusters, which allows a comparison between the two samples.

There is no consensus on the formation of UDGs; present day simulations have proposed several pathways. It has been proposed that UDGs populate the high-spin tail of dwarf-mass dark matter halos, are formed via vigorous star formation feedback and outflows, are formed via effects induced by high-density environments, or are the product of early major mergers that trigger the radial migration of star formation.

Theoretical understanding is hampered by the lack of detailed observations. Among thousands of known UDGs, only a tiny fraction of them have spectra and spectroscopic distance. Furthermore, only a few UDGs have accurate dynamical mass estimates. The first one is DF44 in the Coma cluster, with higher DM content than expected (van Dokkum et al., 2016). The second and third one are NGC1052-DF2 and DF4, a pair of DM deficient galaxies that also have overly luminous globular clusters. NGC1052-DF2 and DF4 have very low velocity dispersion (van Dokkum et al., 2018) which implies a low dynamical mass. The distance to both galaxies have been measured with the Tip-of-the-red-giant-branch method (Danieli et al., 2020; Shen, van Dokkum, & Danieli, 2021) and at ~20 Mpc, their stellar mass alone is enough to account for the inferred dynamical mass. Detailed kinematics revealed the surprising nature of these two UDGs, but their formation mechanism is unclear and we also do not know if their formation is an exception or the norm.

To advance our observations of UDGs, I propose to study both special cases (DF4) and to build a complete sample of nearby UDGs as part of my thesis research. The plan consists of four projects: we will start by measuring the stellar velocity dispersion of DF4 down to very low errors (2km/s). With the

Dragonfly Ultra-wide survey, I will identify a complete sample of nearby UDGs both in the field and in cluster environments. After measuring the distances to the identified UDG candidates, we can then investigate whether DF2 and DF4 are special cases.

Project description

Stellar kinematics of NGC1052-DF4

NGC1052-DF4 is one of the few galaxies known to lack dark matter. van Dokkum et al. (2019) measured the velocity dispersion of the globular clusters in this galaxy and found it to be extremely low, indicating the galaxy has little to no dark matter. However, this velocity dispersion could also be explained if the galaxy has a cored dark matter profile. To distinguish between the stars-only model (which predicts a dispersion of 6-10 km/s) and a cored DM profile (larger than 10 km/s), we need to accurately measure the internal velocity dispersion of the galaxy. Observationally, this is challenging due to its low surface brightness. We used the KCWI spectrograph on the Keck II telescope in its high-resolution configuration to obtain a velocity measurement with less than 2 km/s error.

The other mystery about NGC1052-DF2 and DF4 is their overly-luminous globular clusters. Assuming a typical stellar mass-to-light ratio, this result implies that the GCs are overly-massive. To get an independent mass estimate, we can use the spectral lines of the brightest GC to find its internal velocity dispersion. This goal will be simultaneously achieved with the first one because KCWI is an integral field unit spectrograph, which means that we can extract the GC spectrum from a larger field of observation.

Since the galaxy is faint and we need high signal-to-noise for both goals, we observed the galaxy for two whole nights in November 2021. I carried out the observing program remotely. After the observations, I will use the existing KCWI data reduction pipeline to extract the spectra and fit the velocity dispersion.

Ultra-diffuse galaxies in the Ultra-wide survey

Only a few UDGs have been studied in detail because their low surface brightness poses a challenge for measuring kinematics. Yet, the UDGs with detailed analyses are all special in some way: NGC1052-DF2 and DF4 lack dark matter, while DF44 has too much dark matter. Does that mean dark matter anomalies are common in UDGs? We need a larger sample of UDGs that are easy to follow up. I propose to find all nearby UDGs in the northern sky using the Dragonfly Ultra-wide survey.

Dragonfly Ultra-wide is an all-sky survey optimized for low surface brightness imaging. Compared to existing UDG surveys which focus on distant UDGs in clusters, our project will focus on nearby objects with large angular size. These large diffuse galaxies have not been previously identified because existing sky surveys are not optimized for large objects. The current UDG catalogs include sources up to ~ 20” in diameter but they cannot reliably handle sky subtraction issues. The Dragonfly telescope has an advantage due to its well-characterized point-spread functions and large field of view. Thus, our survey will identify nearby UDGs and build a complete sample out to around 10 Mpc.

Operationally, I will develop an algorithm to analyze the images and detect UDG candidates. The data reduction pipeline, DFReduce (Greco, van Dokkum, Danieli, Carlsten, & Conroy, 2021), has been written by Johnny Greco and the planned footprint will be complete next year. The reduced data will be processed with Multi-resolution Filtering (MRF) (van Dokkum et al., 2020) to remove high surface-brightness compact sources, leaving behind low-surface brightness galaxies to be further analyzed. From that point, I will use Source Extractor to detect remaining sources and develop a custom algorithm to identify UDG candidates.

Distance to Ultra-diffuse galaxies in the Ultra-wide survey

Distance relates the observed properties of a UDG candidate to its physical properties. Only with a reliable distance can we estimate the physical size of a galaxy. However, most of the existing UDG catalogs were identified in photometry data alone and lack distance measurements. This is because the spectral lines needed to measure redshift are weak in UDGs. Due to their low surface brightness and low metallicity, spectroscopic follow-up of a single UDG candidate often requires more than an hour of integration time even on a 8-10 meter telescope. For surveys with hundreds of candidates, obtaining spectra of all the candidates quickly become unfeasible. For the newly identified UDG candidates in the Ultra-wide survey, we will divide them into two groups: those that are located close to clusters and groups, and those in the field. We will obtain distances for both groups using the following methods.

For UDG candidates in clusters, we pioneered a new wide-slit technique on Keck/LRIS. In contrast to traditional 1" slits, our customized slits can be 10" wide to match the size of the UDG candidate and collect most of the light from it. Even though spectral resolution will decrease, it will not significantly impact our target Ca II H and K lines because these lines are saturated. We tested the new slit design in Spring 2021 and successfully observed Coma cluster UDGs in half an hour each. The goal of these observations is to obtain a rough velocity and confirm whether the candidate belongs to the nearby cluster or group. If so, we will use the cluster distance as the UDG distance estimate.

For UDG candidates in the field, we can use surface brightness fluctuation or (preferably) the tip of the red giant branch (TRGB) method to measure the distance. The TRGB method is a well-established distance indicator, and I used this method to measure the distance to NGC1052-DF2 (Shen, Danieli, et al., 2021). For galaxies around 10 Mpc, one to two orbits of HST data is sufficient. We will check if the candidates fall within existing HST datasets, and if not, we can use ground-based data with the surface brightness fluctuation technique. This technique works well for semi-resolved galaxies at our expected distance.

After obtaining distances to our UDG candidates, I will publish a catalog of confirmed UDGs with their physical properties. This confirmed sample can be used to address a range of science questions, and I describe one possible project next.

Do GC-rich UDGs always lack dark matter?

The two UDGs known to lack dark matter both have abnormally luminous GCs. Does this indicate a link between overly luminous GCs and the overall DM content of UDGs? So far, the theory papers proposed very specialized explanations for these galaxies because they are the only ones known. We can begin to answer this question using the UDG sample of Project 3. Specifically, we will identify GCs which are too bright given their distance. Then, we will use Keck spectroscopy to study the kinematics of their host UDGs and get the DM content from a velocity dispersion measurement. If we find other UDGs with DM deficiency and bright GCs, that would mean the formation process of DM deficient galaxies also needs to explain overly luminous GCs. If DF2 and DF4 are the exception, then it indicates that they lost their DM or formed GCs in a rare scenario and is not generally applicable.

Timeline

- November 2021 – March 2022: KCWI observation, followed by data reduction and analysis
- Mid 2022 – 2023: Ultra-wide survey complete, Project 2
- 2023 – 2024: Project 3
- 2024 – 2025: Project 4

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